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Magnetic Field Induced Vertigo in the MRI Environment

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Abstract

This review discusses the theory behind, and the experimental evidence for, the perception of vertigo in a high magnetic field found in an MRI environment. Recent experiments have shown that there is an eye nystagmus response that is proportional to magnetic field exposure and not purely one of rate of change of magnetic field. The mechanism of transduction can be attributed to the Lorentz forces on the endolymph in the ear canals, producing a static pressure due to the vector product of the magnetic field and current density. The adaption and response of the measureable effect reveals time constants which support such a mechanism and explain why the balance system responds in the way we observe and feel. The position and movement of the head relative to the direction of field is of fundamental importance to the sensation of vertigo, as are ambient conditions such as lighting levels. Recent surveys of subjects undergoing seven tesla or higher MRI scans report that, although there is a high perception of vertigo-like effects, these are not intolerable and are not generally the cause of subject withdrawal. This review argues that the ICNIRP guidelines on low frequency fields still need to acknowledge the role of a high magnetic field in producing vertigo sensations rather than rate of change of field alone.

Keywords:

Magnetic Fields, Vertigo, Lorentz Force, Magnetic Resonance Imaging

Introduction

Over the last decade there has been a steady increase in the number of magnetic resonance imaging (MRI) facilities having scanners operating above three tesla. There are around 40 seven tesla systems world-wide, together with a small number of scanners operating at 9.4 tesla or above, mainly within research focussed environments. So far, the effects of time-varying magnetic fields used for MRI have been largely understood: being a function of induced currents in the case of magneto-phosphenes, peripheral nerve stimulation (PNS) and RF heating (depending on the specific absorption rate (SAR)). Static fields (including natural movements in them) present something of an unknown in terms of interactions with the human body. Despite much research over the years, only a few biological effects due to high fields have been reliably observed *in-vitro*, and none *in-vivo* (as yet). However, users of high field systems do report feeling slightly dizzy or disorientated. Whilst not a true clinical definition of 'vertigo', it is useful to describe these non-veridical sensations with such a term. In its mild form, and probably the most common, it is just a sensation that something is 'not quite right'. In the worst case, operators and service personnel working in and around the bore of a 7 T magnet for a long period can be overtaken with nausea related to motion-sickness, necessitating a recovery period away from the magnet. It was initially thought that movements in the magnetic field, and therefore the small electrical currents induced in the head or the fluids of the semi-circular canals, were the cause of Magnetic Field Induced Vertigo (MFIV). A similar effect is that of a Lorentz force acting on the ionic currents flowing in the endolymph of the vestibular system. Another candidate mechanism was susceptibility related forces in the vestibular maculae.

In this review the physical basis for the biological effects is described together with a brief description of the inner-ear. The evidence for each possible interaction mechanism is discussed in the light of experimental evidence. As the user-base of 7 tesla installations has increased, it is now possible to find literature reporting subjective experiences. These data are usually collected from the subjects undergoing the study itself. What is still lacking is any reliable evidence for vertigo effects on operators and this review deliberately does not tackle the issue of exposure on cognition, although some effects might be mediated through a balance mechanism [1, 2]. This review concludes with a discussion on how the current understanding of MFIV is informing the regulatory framework related to magnetic fields.

Human Inner Ear Physiology

The inner ear comprises the cochlea (responsible for hearing), three semi-circular canals each incorporating an ampulla which houses the cupula and hair cells (responsible for rotational velocity sense), and saccules containing the maculae which are responsible for gravitational orientation and linear accelerations. The maculae are L-shaped plates having embedded otoliths (calcium carbonate crystals) to give mass. The shape of the two maculae allows all three linear acceleration directions to be measured giving a person orientation information. The positional displacements of the cupulae and maculae are sensed by hair cells. In both cases the hair cells are biased into a linear region of operation and are able to adjust their firing rate according to both positive and negative displacement. A high potassium ion-flux maintains this bias (called the dark current) and is supplied by stria cells on the walls of the ampulae and saccule. Usually, the inertia of the fluid in the canals due to angular acceleration creates a pressure on the cupula causing it to deflect slightly which is then sensed by the hair cells. The normal cupula forms a sealed flap across the ampula. The geometry of the canal, the viscosity of the endolymph, and the spring constant of the cupula result in a system which responds as an integrator of the inertial acceleration, therefore acting as a sensor of angular velocity (for normal movements of the head).[3, 4]

Magnetic Field Interactions with Matter

Magnetic Susceptibility

Biological materials have a magnetic susceptibility χ which is small and can be either positive (paramagnetism) or negative (diamagnetism). For most materials magnetic susceptibility is measured in parts-per-million. Placed in a strong inhomogeneous magnetic field, a diamagnetic material will be subject to a force directed towards a lower field region. The force on an object having a difference in susceptibility from the surrounding medium $\Delta\chi$ is $\mathbf{F} = \Delta\chi\tau\nabla(\mathrm{B}^2)/2\mu_0$, where τ is the object volume, $\mu_0 = 4\pi\ 10^{-7}$ N/A² is the permeability of free-space and B is the magnitude of the magnetic field. A field-gradient product of 1470 $\mathrm{T}^2\ \mathrm{m}^{-1}$ would produce a force sufficient to balance the force due to gravity and potentially 'levitate' water or biological tissue.

Electric fields induced by movement in a magnetic field

In a conductive medium the current density, $\mathbf{J}$, is given by the electric field, $\mathbf{E}$, multiplied by the conductivity, σ. The general expression for induced electric field may be given by, $\mathbf{E} = -\nabla\mathrm{V} - \partial\mathbf{A}/\partial\mathrm{t} - \mathbf{v}\times\mathbf{B}$, where V is a scalar potential and $\mathbf{A}$ is a vector potential such that the magnetic field, $\mathbf{B}$, is defined as $\mathbf{B} = \nabla\times\mathbf{A}$. For an isolated, rigid body moving at velocity, $\mathbf{v}$, in a static magnetic field only the final term is non-zero. Translational movements in an in-homogeneous, or rotations in a uniform, magnetic field can equally give rise to an induced electric field. In low conductivity biological tissues, where σ is of order unity, the main magnetic field is not perturbed by the additional magnetic field caused by the current density itself. The middle term (i.e. time-varying magnetic fields) gives rise to the driving term which results in PNS and SAR.

Magneto-Hydrodynamics

Magneto-Hydrodynamics (MHD) usually relates to a conductive fluid flow, and the modification of that flow by the presence of a magnetic field. If the current induced by movement of a conductive medium in a magnetic field is large enough, then the current itself generates a magnetic field which will oppose the main magnetic field. The net force is given by the volume integral of the Lorentz force $\mathbf{F} = \int(\mathbf{J}\times\mathbf{B})\mathrm{d}\tau$. For fluids this force can be added into the Navier-Stokes' flow equation. Hence a net increase in pressure can be calculated for a given flow velocity and magnetic field. If there is an external applied net potential, V, driving a current density, $\mathbf{J}$, through the medium, then there will be a force generated which is perpendicular to both $\mathbf{J}$ and $\mathbf{B}$.

Magnetic Field Induced Vertigo

In a series of informative animal experiments, rodents show circling behaviour and taste aversion after exposure to magnetic fields [5, 6]. After removal of the labyrinth, rats are oblivious to the field exposure. The vertigo effect has thus been confirmed as an action of the magnetic field on the primary transducer – rather than directly on the Central Nervous System (CNS)[7].

In the light of the physics of magnetic field interactions, it is now possible to discuss four likely candidates for the sensation of MFIV which have their origins in the vestibular system: forces due to the susceptibility of vestibular structures; current flow due to a net rate of change of magnetic flux; MHD due to head movement [8, 9] and fluid pressure due to Lorentz forces [10].

Susceptibility-induced Forces

The force due to differences in magnetic susceptibility (and density) between the vestibular endolymph and the cupulae or maculae structures generate a mechanical displacement which would be sensed by the brain as an effective motion. The otoliths which make up the utricle and saccule maculae have a susceptibility and density close to that of the aragonite form of calcium carbonate. For these structures, a magnetic field gradient product of 46 T^2 m^{-1} produces a perceived acceleration of 0.1 m s^{-2} [9]. This mechanism would imply that a subject could sense (but not necessarily perceive) an effective acceleration in areas where such a field-gradient product exists – even if the subject is not moving at all. In the case of a 7 T magnet this field-gradient product is similar to the maximum value on-axis just inside the bore. The sign of the effect would indicate that the perception of acceleration would be towards regions of higher field. In addition the polarity of the field is not relevant to the polarity of the effect - as the forces are dependent on the spatial derivative of the square of the magnetic field magnitude. For the cupulae, the perceived rotational acceleration in a similar magnetic field gradient may be assumed to be negligible because the gel-like structure of the cupula has a similar susceptibility and density to that of the surrounding fluid. The susceptibility mechanism is a strong candidate as there are a small number of subjects who claim to be 'falling' when standing adjacent to a 7 T magnet. This can be measured by monitoring their postural sway whilst they fix their gaze on a spot whilst opening and closing their eyes. Subjects report a sudden onset of the effect near the magnet as would be expected with an effect related to the square of the magnetic field [9].

Magneto-hydrodynamic Effect (MHD)

The net pressure due to velocity-generated magneto-hydrodynamic effects can be calculated for given angular accelerations. For a fluid-filled toroid, representing the semi-circular canal, the pressure generated is mostly radial which does not couple to the cupula in that canal. Induced pressure will also largely cancel in orthogonal canals. Calculations of the effective pressure indicate that even for high magnetic fields (> 4T) the effect would only be at the limits of perception for very high angular accelerations such as vigorous shaking of the head [8]. This mechanism does not have any experimental support as real effects are perceived at very low frequency of movement, or even when the subject is stationary.

Galvanic vestibular stimulation (GVS) and inner vestibule stimulation experiments demonstrate the linearity of hair cell nerve firing and subject response directly modulates the firing rate of the cell. Hence it is possible to hypothesise that quite small rotations and movements in the magnetic field can generate electric fields of the order of magnitude to generate the GVS effects. Experiments in a 7 tesla magnetic field show that a magnetic field change of the order of 4 tesla during a period of 2 seconds are required for subjects to perceive an effect [9]. This measured response of subjects is sensitive to the polarity of the field as well as the direction of travel. The sense of the direction of perception of movement reverses if the sense of the current flow around the head reverses. However, it has been noted that large peak rates of change of magnetic field are not in themselves enough to induce vertigo [9], leading to the anomaly that vertigo can be perceived by a subject at head rotation velocities and accelerations which are a lot lower than are expected from calculation.

Roberts *et al* [10] demonstrated that horizontal slow-phase eye nystagmus velocity (H-SPV) produced by exposure to a strong magnetic field is directly proportional to the magnetic field strength, with a response which has an adaption component and a linear response to field. This linear response measurement provided a new and vital piece of objective evidence. The experiment does not depend on a scored subjective response as the subject has no control over the reflex if there is no visual reference. They measured the SPV of the eye nystagmus in the dark as a function of time and related it to the applied magnetic field. A set of data obtained by the author of this review, which reproduces this experiment, is shown in Figure 1. These data show the initial response to the magnetic field change and the slow adaption process which does not return to zero until the subject is removed from the field. The adaption (habituation) process takes place in the hair cell nerve afferents is shown occurring both after the start of the exposure period and after the field reduces to zero. Subjects report a reversal of apparent rotation during this latter period when compared to the initial exposure period response. Additionally Roberts *et al* proposed a mechanism based on a Lorentz force, where the current does not come from induction but that the dark current has a high enough current density to elicit a pressure change in the semi-circular canals. Antunes *et al* [11]refined the calculation by Roberts *et al* by modelling the canals, currents and forces and confirmed that this mechanism is plausible and gives a realistic prediction of both the magnitude and direction of perception. As the Lorentz force is dependent on magnitude and directions of both magnetic field and orientation of the cupula then the SPV response is highly directional with both peaks and nulls in the response dependent upon head orientation [10, 12]. The dynamics of the response may be modelled in terms of a low pass and high pass (partial) adaption model. The time constants of the model used to fit to experimental data give characteristics similar to those measured experimentally for rotational motion [13] and shown in Figure 1. These data fit a mechanical transduction model for the canal-cupula system which includes a partial habituation stage based on a hair cell response. Using the Lorentz mechanism as a model it is possible to explain the pattern of responses measured in previous studies. For example it explains why a slowly changing field can elicit a strong response, determines how the 'polarity' of response varies and why there is a response to a field. The habituation mechanism explains the reversal in polarity after the exposure returns to zero.

Subject Response

Physiological Response

Ward *et al* [14] produce further compelling evidence for a Lorentz force mechanism. Firstly they demonstrate that subjects without any vestibular function show no response, and subjects having a unilateral functional deficit have a modified response consistent with the orientation of the head in the magnetic field as expected from the model. These authors also raise the possibility of using magnetic fields as either a diagnostic tool to assess vestibular function, either in the clinic or for vestibular function research. Effectively the magnetic field provides a rotational velocity profile that it is not possible to generate mechanically. Theysohn *et al* [15] demonstrate that there is a significant postural sway effect (employing Unterberger's stepping test) 1 minute post exposure to a 7 tesla magnetic field which is absent 15 minutes later, and not observed at all for exposure to 1.5 T.

They also note that very short exposures do not elicit a sway response. Such an observation is entirely consistent with an adaption mechanism. In a paper by van Nierop et al [16] postural body sway is measured outside a 7 tesla magnet at magnetic field strengths of the order of 0.5 T and recorded rates of change of 0.7 T s^{-1}. Their conclusion was that body sway area had a significant correlation with exposure and that this was on a par with a blood-alcohol concentration of 0.09% which would be well above the maximum legal limit for driving in the UK. The authors aim was to assess the effect of magnetic fields (static and time-varying) on human performance (e.g. surgeons performing interventional MRI) rather than determine a mechanism of interaction.

Acceptance by Subjects

Since the introduction of the first high-field (7 T or above) scanners, there are now a number of studies which report on the acceptance of 7 T (or 9.4 T) amongst both clinical and healthy volunteer subjects. These studies attempt to understand the influence of the higher field on aspects of the scan experience such as claustrophobia, PNS, RF SAR etc. Some of the questions posed to subjects, depending on study, ask about the prevalence of vertigo or movement-like sensations. It is important to note that, amongst most of the studies cited below, there is no mention of, or recording of, the lighting used, or the state of the subject's eyes (open, closed). To elicit SPV nystagmus there is a requirement for the subject to be in total darkness. Sensations of non-veridical movement (leaning, bending, curving) are largely suppressed if there are visual cues [12]. Hence, in the dark nearly 100% of subjects report sensations [12], but only around 15 – 25% of subjects notice these effects in the ordinary light conditions in the reports cited. This discrepancy highlights the difference between findings of experiments which test mechanisms and those which are looking for responses during standard protocols. In addition, the standard protocols are carried out with the subject supine in the normal scanning position, whereas the maximum vertigo response might be with the head pitched upwards with the body prone [12]. There is, undoubtedly, an effect linked with head attitude and even body position. These latter effects are more likely to be relevant to operators (and hence of interest to regulators) than the responses of subjects being scanned.

One of the first papers to appear on the levels of acceptance of 7 T MRI was by Theysohn *et al* [17] which reported vertigo sensations in 26 % of subjects (N = 142) with 5 % rating it as very unpleasant. These figures appear to be consistent across a range of subsequent studies. However, in these various studies the questions used and subjective grade scales range from simple yes-no [18] to more complex grades[19]. In the Uwano *et al* study [19], reports of vertigo or non-veridical movements (such as 'curving' or 'leaning' which are perceived during magnet entry) are reported in around 10 % of subjects. This is lower than in previous studies, but could occur for a number of reasons, such as the lighting conditions as well as head positioning. Another more subtle reason, demonstrated in a single-centre study by Cosottini *et al* [20], is an apparent decline in scores to a lower reporting of vertigo by subjects across the study. They attribute this to a better understanding of the effects by operators. This is possibly the first measured evidence of something which is largely anecdotal amongst the high-field community – that operators adapt their behaviour to, and expectations of, working in and around high-field magnets. However, this 'expectation' seems to have transmitted itself to the subjects. It may be that the way subjects are treated or that information given, either unconsciously or deliberately, reduces anxiety about the perceived movements and increases acceptability. Studies such as those by Rauschenberg *et al* [21] and Uwano *et al* [19] discriminate between the periods where subjects are being moved into the magnet and periods where they remain stationary in the static field (during the scanning process). Clearly the vertigo effect is lower whilst at iso-centre (during the scan) but can clearly be explained by the adaption process and the static field Lorentz mechanism so there is no inconsistency. Uwano *et al* [19] attribute the high degree of acceptability and tolerance to vertigo amongst subjects to a low table speed. If the introduction time is of similar order to the adaption time (of order 40 – 100 s) then the perception will be minimised. Rauschenberg *et al* [21] (surveying responses from over 3000 subjects) also compare data from subjects undergoing scans at the higher field strength of 9.4 tesla. A higher level of discomfort related to vertigo at the higher field was recorded but did not lead to a higher rejection rate by subjects.

It is not known, as yet, what the subjective effect of high magnetic fields might be on children. The only paper to broach this subject by Chou *et al* [22] ‘interpolate’ a level of acceptance from responses of experienced adults. There is certainly no reason to worry regarding likelihood of damage to the vestibular system as any of the mechanisms discussed above point to the vestibular system working well within its dynamic range. However, the variation observed in the magnitude of the SPV responses across the measured populations are large – it is not known at present if these vary with age of subject.

Vertigo and Regulation

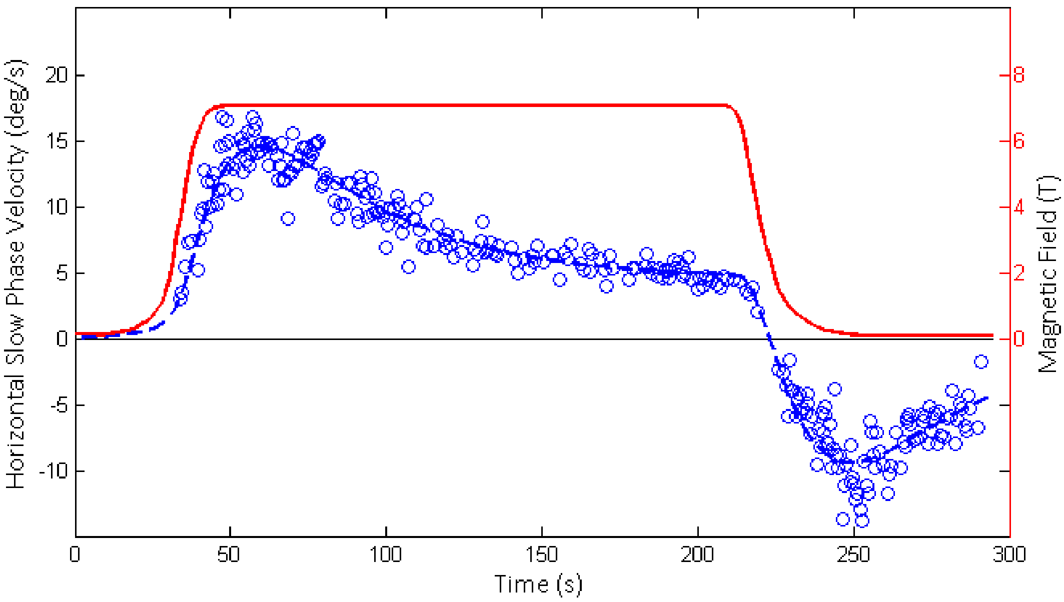
The electromagnetic spectrum is a continuum and the biological response to electric and magnetic fields varies markedly with frequency. It is only necessary to look back at the physics behind the interactions to see a complex picture of interconnected effects. Regulators need to describe the limits in terms of magnitudes and frequencies of the applied level. Mostly, for PNS and SAR, a set of general limits can be applied and the scanner set to work within prescribed levels. What is more difficult is to prescribe regulatory limits for operators and other personnel using the scanners. Defining the experienced field, measuring it and imposing limits upon its maximum value is a difficult proposition and has been discussed in detail by McRobbie [23] and Yamaguchi-Sekino *et al* [24] for example. Following the publication by the International Commission on Non-Ionizing Radiation (ICNIRP) of its guidelines on 0 – 1 Hz magnetic fields [25], Gowland and Glover [26] argue that these proposals do not take account of the most recent understanding of vertigo mechanisms, but rather that the proposed action levels therein are based on data published in 2007 [9]. Whilst not incorrect, this data should be interpreted in the light of more recent findings which support a Lorentz-force-mediated mechanism. In response ICNIRP [27] argue for further studies and that restricting a change in magnetic flux of 2 tesla over 3 seconds is an acceptable compromise. What this guideline effectively does not acknowledge is that to lead to vertigo this change in field is only valid if there is a high field ‘baseline’. For example a rotation of the head going from plus to minus 1 T in 3 seconds would not elicit an effect but going from 1 to 5 tesla in 6 seconds would give a perceivable effect. The rate of change would be the same. There needs to be more emphasis on the absolute fields encountered, their direction as well as the rates of change within those fields. An understanding of the role of training and adapting behaviour in and around MRI installations may be more useful than a numerical action value.

Conclusions

It appears from the experimental evidence that the major sensory effects observed at field strengths less than 8T are mediated through a Lorentz force acting on the dark ionic currents in the vestibular system. These effects are larger and more sustained than electric fields which are induced by rotation or translation of the subject in magnetic fields. Magnetic susceptibility of sensory tissues in the vestibular system may also be responsible for a magnetic field effect on humans, but this is likely to be translational rather than the experimentally perceived rotations. MHD due to movement is unlikely to have a role in such small vestibular structures. There is no need to invoke a direct magnetic effect on the CNS. There is agreement across a number of surveys involving a total of over 4000 subjects that the incidence of vertigo or non-veridical perception at high fields (>3 T) is about 10 to 25 % but this will depend on local conditions, protocols and positioning of subjects. A better understanding of high field effects by operators and other personnel may lead to a reduction in the anxiety about vertigo effects. There is no evidence of long-term (beyond 20 minutes after exposure) of a vertigo effect on balance or sway. A high field is a pre-requisite for subject reported vertigo-like effects and although the rate of change of field is important for the perception of that field, a similar rate of change around zero mean or at low field does not elicit the same effect.

List of Figures

Figure 1: The experimentally measured horizontal slow phase velocity (circles) of eye nystagmus as a response to a magnetic field change (solid line and RHS scale). This response demonstrates the adaption phase of the response, the response to a static field (from about 150 to 225 s) and the nystagmus reversal on removal from the field. The dashed line shows the model fit response as described by Glover *et al* [13].



References

The following three references should receive an asterisk and associated textual commentary:

[10] This work marks a breakthrough in the understanding of the vestibular response to high magnetic fields. Not only did it provide new measurements but it also hypothesised the Lorentz force mechanism for the first time to explain the response.

[21] This work is major study covering over 3000 subjects' responses from a number of 7 and 9.4 T installations over a number of years. These responses indicate a high level of acceptance for high-field scanning with around 20% of subjects citing vertigo as being significant. The vertigo effect was more pronounced at 9.4 T than at 7 T.

[20] Reports a high degree of tolerance to high magnetic fields by subjects. Reports an interesting finding that the number of subjects reporting discomfort significantly reduced over the period from installation of the scanner until the writing of the report. The authors ascribe this to 'operator experience'. As the most regularly reported side-effect is vertigo then there must be an assumption that the information given to subjects prior to scanning regarding this effect must be improving.

1. Heinrich, A., et al., *Effects of Static Magnetic Fields on Cognition, Vital Signs, and Sensory Perception: A Meta-analysis.* Journal Of Magnetic Resonance Imaging, 2011. **34**(4): p. 758-763.
2. Schlamann, M., et al., *Exposure to High-Field MRI Does Not Affect Cognitive Function.* Journal Of Magnetic Resonance Imaging, 2010. **31**(5): p. 1061-1066.
3. Oman, C.M., E.N. Marcus, and I.S. Curthoys, *The Influence of Semicircular Canal Morphology on Endolymph Flow Dynamics - an Anatomically Descriptive Mathematical-Model.* Acta Oto-Laryngologica, 1987. **103**(1-2): p. 1-13.
4. van Egmond, A.A.J., J.J. Groen, and L.B.W. Jongkees, *The Mechanics of the Semicircular Canal.* Journal Of Physiology-London, 1949. **110**(1-2): p. 1-17.
5. Houpt, T.A., et al., *Orientation within a high magnetic field determines swimming direction and laterality of c-Fos induction in mice.* American Journal of Physiology-Regulatory Integrative and Comparative Physiology, 2013. **305**(7): p. R793-R803.
6. Houpt, T.A., et al., *Behavioral effects on rats of high strength magnetic fields generated by a resistive electromagnet.* Physiology & Behavior, 2005. **86**(3): p. 379-389.
7. Cason, A.M., et al., *Labyrinthectomy abolishes the behavioral and neural response of rats to a high-strength static magnetic field.* Physiology & Behavior, 2009. **97**(1): p. 36-43.
8. Schenck, J.F., *Physical interactions of static magnetic fields with living tissues.* Progress In Biophysics & Molecular Biology, 2005. **87**(2-3): p. 185-204.
9. Glover, P.M., et al., *Magnetic-field-induced vertigo: A theoretical and experimental investigation.* Bioelectromagnetics, 2007. **28**(5): p. 349-361.
10. Roberts, D.C., et al., *MRI Magnetic Field Stimulates Rotational Sensors of the Brain.* Current Biology, 2011. **21**(19): p. 1635-1640.
11. Antunes, A., et al., *Magnetic field effects on the vestibular system: calculation of the pressure on the cupula due to ionic current-induced Lorentz force.* Physics In Medicine And Biology, 2012. **57**(14): p. 4477-4487.
12. Mian, O.S., et al., *On the Vertigo Due to Static Magnetic Fields.* Plos One, 2013. **8**(10): p. e78748.
13. Glover, P.M., et al., *A dynamic model of the eye nystagmus response to high magnetic fields.* Physics in Medicine and Biology, 2014. **59**(3): p. 631-645.

14. Ward, B.K., et al., *Magnetic vestibular stimulation in subjects with unilateral labyrinthine disorders.* Front Neurol, 2014. **5**: p. 28.
15. Theysohn, J.M., et al., *Vestibular Effects of a 7 Tesla MRI Examination Compared to 1.5 T and 0 T in Healthy Volunteers.* Plos One, 2014. **9**(3): p. e92104.
16. van Nierop, L.E., et al., *MRI-related static magnetic stray fields and postural body sway: A double-blind randomized crossover study.* Magnetic Resonance In Medicine, 2013. **70**(1): p. 232-240.
17. Theysohn, J.M., et al., *Subjective acceptance of 7 Tesla MRI for human imaging.* Magnetic Resonance Materials in Physics Biology and Medicine, 2008. **21**(1-2): p. 63-72.
18. Klix, S., et al., *On the Subjective Acceptance during Cardiovascular Magnetic Resonance Imaging at 7.0 Tesla.* Plos One, 2015. **10**(1).
19. Uwano, I., et al., *Assessment of Sensations Experienced by Subjects during MR Imaging Examination at 7T.* Magnetic Resonance in Medical Sciences, 2015. **14**(1): p. 35-41.
20. Cosottini, M., et al., *Short-term side-effects of brain MR examination at 7 T: a single-centre experience.* European Radiology, 2014. **24**(8): p. 1923-1928.
21. Rauschenberg, J., et al., *Multicenter Study of Subjective Acceptance During Magnetic Resonance Imaging at 7 and 9.4 T.* Investigative Radiology, 2014. **49**(5): p. 249-259.
22. Chou, I.J., et al., *Subjective discomfort in children receiving 3 T MRI and experienced adults' perspective on children's tolerability of 7 T: a cross-sectional questionnaire survey.* Bmj Open, 2014. **4**(10).
23. McRobbie, D.W., *Occupational exposure in MRI.* British Journal Of Radiology, 2012. **85**(1012): p. 293-312.
24. Yamaguchi-Sekino, S., M. Sekino, and S. Ueno, *Biological Effects of Electromagnetic Fields and Recently Updated Safety Guidelines for Strong Static Magnetic Fields.* Magnetic Resonance in Medical Sciences, 2011. **10**(1): p. 1-10.
25. Ziegelberger, G., *ICNIRP Guidelines: For Limiting Exposure to Electric Fields Induced by Movement of the Human Body in a Static Magnetic Field and by Time-Varying Magnetic Fields Below 1 Hz.* Health Physics, 2014. **106**(3): p. 418-425.
26. Gowland, P. and P. Glover, *Comment on ICNIRP Guidelines for Limiting Exposure to Electric Fields Induced by Movement of the Human Body In A Static Magnetic Field and by Time-Varying Magnetic Fields Below 1 Hz.* Health Physics, 2014. **107**(3): p. 261-261.
27. Ziegelberger, G., *Response by ICNIRP to the Comments of Gowland and Glover.* Health Physics, 2014. **107**(3): p. 262-262.